

INSTITUTE
OF
HYDROLOGY

THE TRANSLATION OF MICRODATA
STYLE AUTOMATIC WEATHER
STATION DATA

by

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ABSTRACT

This Report describes the software available at the Institute of Hydrology for processing cassettes containing data recorded on Microdata loggers by the Institute's automatic weather stations. The translation of the cassettes proceeds in two stages which are described separately:

Transferring the data to a computer readable medium;

Producing listings of the data, including presentation of hourly and daily means and totals of the parameters measured by the stations, and evaporation rates estimated using both Penman and Penman-Monteith approaches.

The abstraction of information from data recorded by Microdata loggers in other applications is also discussed briefly, as is the use of an oscilloscope whilst translation proceeds to recognize various logging equipment malfunctions.



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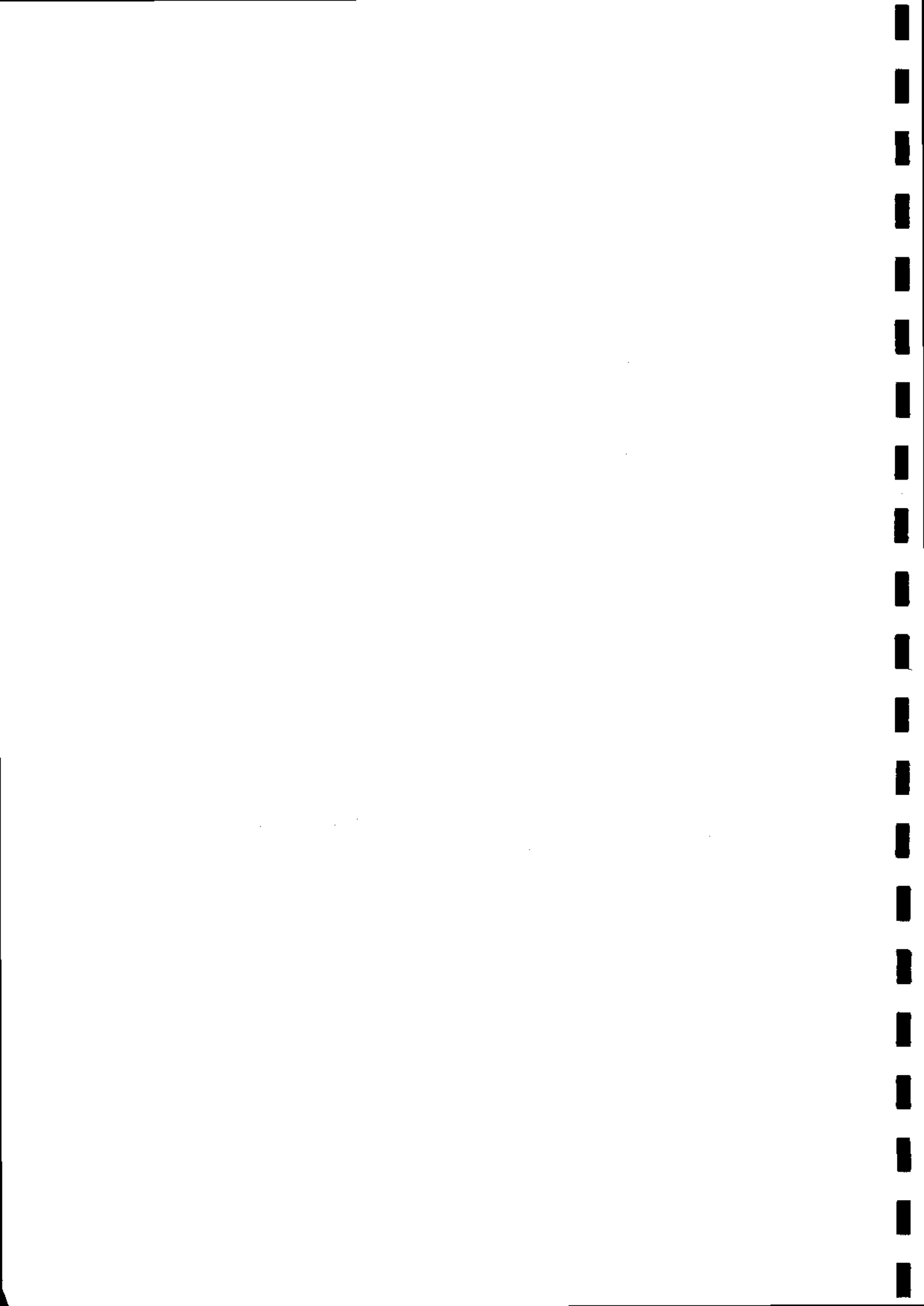
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1. INTRODUCTION

The Institute of Hydrology now operates about 30 automatic weather stations⁽¹⁾ in Britain and overseas. Data are logged on compact magnetic tape cassettes (normally C60) in the field using the Microdata logger system. Other applications such as automatic river level recorders, rainfall event recorders, soil temperature recorders, heat flux plate measurements, etc are also a source of cassettes from remote places where a mains electricity supply is not available. The cassettes from all such instruments are returned to the computer unit at Wallingford where a PDP8 and a PDP8/a are used to translate the data held on the cassettes into the form which research scientists require for use in their calculations.

Alongside the developments in the stations' hardware over the last ten years, considerable effort has been put into the complementary computer software described here. The cassette translation process takes place in two steps. Firstly, the data are transferred from the cassettes (which cannot be read by a computer cassette system because they are not written according to an accepted computer standard) on to some computer readable medium (magnetic tape) as described in Section 2. Subsequently the information on the magnetic tapes can be processed by a program suitable for the type of instrument involved; in the case of automatic weather stations this entails producing listings of the hourly and daily averages or totals of the parameters measured by the stations and the estimation of evaporation rates as discussed in Section 3. Other programs exist for other instruments but are not described here.

2. TRANSFER OF DATA FROM CASSETTE TO COMPUTER READABLE MEDIUM

The data on the cassettes are read through a Microdata reader interfaced to one of the Institute's DEC PDP8 computers. The program which controls this process is written in the PDP8 assembler language PAL 111 and can only be run on the PDP8 series computers. A high level language was not used for this purpose because DEC FORTRAN could not handle interrupts from peripherals in real time. The output computer medium may be either DECtape, which is standard, or in special cases may be 7-track NRZI industry compatible magnetic tape. In both cases the data are grouped into hourly blocks containing the data from 12 scans which are taken at 5-minute intervals. Similarly, in both cases the block size is 128, 12-bit words and the first scan in each block is the one taken on the hour.

Where DECtape is used as the output medium, a special format is used for the DECtape. Block 1 is always used as a directory. This contains information about the weather station and an identifier which was

introduced to reduce the risk of accidental overwriting of data tapes with information from a different site or instrument type. The directory also holds the number of cassettes translated on to the DECTape, together with the starting times and dates of these cassettes and the block numbers which hold the data from each cassette. A DECTape has a capacity of 61 days only, but most cassettes are run for 14 or 21 days. Since data cannot be spread over two DECTapes, the 14-day period is more efficient in terms of DECTape utilisation.

Block 2 on the DECTape is used as the "carry-forward" block. It stores the data from the hour at the end of a cassette if that hour's data is not complete, ie for any cassette which ends on or before 50 minutes past the hour, the part hour is written to block 2. This information can then be retrieved and added to the start of the next cassette from that station. If a cassette does not start on an hour, or have retrievable data for the first part of the first hour, the missing scans are padded out with zeros to maintain the time sequence within a block.

Note that on magnetic tape there is no directory because the tape does not have pre-structured blocks, that there is no retrieval of data, and also that the last part hour is appended to the rest of the data.

Because of the diversity of weather stations in the field, the PDP8 operator has to inform the translation program of the number of channels on the station: this is usually 8 or 9 and must not exceed 10 because then the 128 word block on the DECTape would be exceeded. (Entering 0 channels is a special case described below). Independent of the number of channels on a station, 12 scans are written to each block which is padded up to 128 words with zeros as necessary. Before a translation begins, the operator must also enter the start time and date of the cassette data for insertion into the directory after tape validation is successful. The blocks which will be used on the DECTape are determined by reference to the directory without operator intervention.

As well as making a copy of the cassette's data on to the output medium, the program also does simple format checking and attempts to keep time synchronisation good through badly written patches of data. The logic of the program assumes that channel 1 on the weather station is 'scan marker' (which is a measurement of a reference voltage within the logger) which should normally be 240 logger steps. Any number over 220 is acceptable in the standard program, but this limit can be changed manually if required for stations which have malfunctions, eg, abnormally low scan marks, or data channels which exceed 220 either because of electronic failure or parameter values outside the design range. These checks can be turned off by entering 0 as the number of channels on the logger, but this also turns off the hourly blocking of data (data is then entered into the block until it is full, regardless of errors) which means it cannot be processed by the programs discussed in Section 3.

Errors detected in the data are classified by four types and the data patched up accordingly. For a logger with N channels these are:

- i. Short scan. This is recognised when a scan marker occurs within N data words of another scan marker. When this happens, the scan with the missing channels is padded out with 2046(s) until the required number of channels is reached; the scan marker just found is the new reference scan marker. Finding one or more 2046 at the end of a raw data scan is an indication of missing channels but does not identify which channels are missing.
- ii. Missing scan marker. This is diagnosed when the separation of two scan markers is $2N-1$ words. The program then inserts a dummy scan mark of 240 at the start of the second scan and adds 512 to the last channels of both scans. It is then up to the analysis program to detect these error identifiers and decide whether to accept the data channels as valid or not (obviously having to subtract the 512 from the last channels if accepting them).
- iii. Single extra channel. This is assumed if two scan markers are separated by $N+1$ words. In this case the N^{th} word in the sequence is discarded, 512 added to the $(N-1)^{\text{th}}$ word (last word in the assumed real scan) and the new scan mark taken as reference.
- iv. Other errors. When two scan markers are $\geq N+2$ words apart (except $2N-1$: see ii), it is assumed that some compound error has occurred including the loss of a scan marker. Here 240 is inserted every N^{th} channel of such data and the apparent last channel of each scan has 512 added to it. If the last scan is left incomplete by this procedure, it is then padded out with 2046(s).

In this way it is hoped to preserve the time synchronisation of the data as far as possible, as well as identifying any errors at this stage. There is of course no guarantee that the errors diagnosed are those which actually occurred, and errors of type iv) can be difficult to explain.

As translation proceeds, the teletype bell is sounded or '?' is printed as each error is detected as an audible warning to the operator that something is amiss. Also the accumulated number of errors is shown in the bulbs of PDP8's multiplier quotient register display. At completion of translation, the DECTape directory is updated, the carry forward block is written - (if the last scan is for 55 mins past an hour a message is typed on the teletype to warn the operator that there is nothing to carry forward). The accumulated number of errors classified by type is listed; this is followed by a frequency histogram of the occurrence of each number above 220 as scan marker. (Because of the PDP8 word length, no number is allowed to exceed 4096 in this printout). Figure 1 overleaf shows an example printout; it can be seen that this is from a well set up logger because the distribution of scan mark channel contents is narrow and centred on 240 logger steps. Any

.R MT

IOH MWS PR1

[illegible]

ABORT THIS FILE?N

FIGURE 1 Typical teletype printout produced during cassette translation

deviation from this pattern is an indication of some problem. This may be a channel, other than scan mark, having contents greater than 220 (in which case there should be a large short-scan count), or a badly set up logger if the distribution is centred significantly away from 240, or an indication of badly written scan marks (and possibly other channels) if there is a wide scatter of scan mark values. The exact problem can usually be identified by listing the raw data and/or examining the waveform as described in Section 5. Once the problem is identified the operator can decide the likelihood of a retranslation being successful if, for example, the range of numbers accepted as valid scan marks is changed.

Finally the operator is given the option of "aborting a file" - ie of returning the DECTape's directory to its state prior to the current translation if it is realised that the translation is obviously in error. Also the operator can abort a translation if no data are found on a cassette (data are defined to start with the occurrence of the first scan marker) by setting all the switch register bits on the PDP8.

No analysis of the data during this first stage translation is possible because the time between successive interrupts from the Microdata reader is insufficient to guarantee time for any worthwhile analysis, and there is no way of stopping the Microdata reader under computer control. Transfer between the PDP8 memory and the DECTapes is performed in 5-block transfers using the PDP8's data break facility (Direct Memory access cycle stealing) which does not conflict with the timing requirements of servicing interrupts from the Microdata reader. As each word comes from the Microdata reader, a check is made that the previous word has been dealt with completely, even when the error recovery mechanisms are invoked. If this check fails, the translation is halted. This also happens when an I/O error is detected on DECTape (or Mag tape) because insufficient time exists to do any error recovery on the output peripherals, again a consequence of the inability of the Microdata reader to react to computer control. In any case such I/O errors would probably not be recoverable by the software.

3. PRODUCTION OF LISTED HOURLY AND DAILY TOTALS FROM RAW DATA

Programs to convert the raw data produced by stage 1 of the translation process into listings of hourly and daily averages (or totals as appropriate) of the parameters measured by the automatic weather stations in physical units have been written in FORTRAN. This makes the software easy to modify for different types of station or application and eases problems associated with using the software on different computers. The suite of analysis programs was first written for the PDP8 with a separate program for each type of station due to the restricted core size of the PDP8. This software has now been

transferred to the UNIVAC 1108 at IH and rewritten more generally to cope with the various types of station now deployed and also to compute both Penman and Penman-Monteith evaporation estimates. It should be emphasised that all the programs described in this section deal specifically with data formatted according to the rules given in Section 2. Also note that before data can be analysed on the 1108 it has to be copied from DECTape to 7-track magnetic tape. The rest of this section describes in detail the UNIVAC version of the program which produces output as shown in Figure 2 opposite.

The suite of routines comprises

- a. **MAIN**, the main routine which initialises the program, reads the data cards which supply information about the station and the data set to be analysed. It also reads from cards any data from a previous cassette which are to be included with the present data set in the calculation of daily averages for the first day, and prints the data which can be carried forward to be included with subsequent data. It prints the information supplied on the data cards, and headings and summary information at the end of the cassette. The format of the data cards and the information they supply is specified in Appendix 1.
- b. **TAPSKP (NOFF)** which is a subroutine to skip over NOFF blocks (hours) of data on the magnetic tape before beginning analysis. NOFF is supplied on data card 1.
- c. **TPREAD (128, ID)** This subroutine is written in UNIVAC assembler, and its equivalent will be needed to run the suite on any other manufacturer's equipment, or if any other input medium is to be used. TPREAD reads one block per call of the non standard magnetic tape produced by the PDP8 and converts the 128 (12 bit) words of information corresponding to one hour's data into 128 36 bit words in UNIVAC core in the FORTRAN array ID. It also sets ID(1) to minus the status returned by the UNIVAC tape reading routine in case of error; specifically ID(1) is set to -1 if an End-of-File-mark is encountered on the magnetic tape.
- d. **CLOCK** is a subroutine which adds one hour to the current time and date, except on the first call when it adds NOFF hours. It also resets the FORTRAN variable MINS to zero.
- e. **RAWD** is a subroutine which is called 12 times for each block of data read by TPREAD, that is once for each data scan. On each call, 5 minutes is added to the time. RAWD has one of two further functions depending on the value of MODE supplied on data card 1. These are:

MODE = 1 Print raw data scans in logger steps with times appended for the number of hours specified by NH (on data card 1), having skipped over NOFF hours from the start of the data.

THIS IS A DIDCOY TYPE AUTOMATIC WEATHER STATION

SENSITIVITY OF DEPRESSION CHANNEL IS .055 DEG C/STEP
SENSITIVITY OF TEMPERATURE CHANNEL IS .200 DEG C/STEP
ZERO TEMPERATURE IS AT 50. STEPS
BUCKET SIZE ON RAINGAUGE IS .5 MM

HOURLY & DAILY DATA

MOLECULAR FACTOR = 128 NET FACTOR = 94

VALUES TAKEN FOR RS ARE:-

D. O. O. 0. 35. 35. 40. 40. 45. 50. 50. 65. 70. 70. 70. U. O. U. SEC/M

R.A = 5.0 SEC/M; PSYCHROMETRIC CONSTANT = 1232.00/LAMBEA PER DEGREE C
STATION ALTITUDE IS 1220.M AND STANDARD ATMOSPHERIC PRESSURE IS 873.SMB

HOUR	SOLAR FROM	SOLAR W/M**2	NET	DEP	TEMP DEG C	SPEED M/S	OIRN DEGS	RAIN MM	GDD SCANS	LAMBDA*E W/M**2	Q X10**3	SHD X10**3	DEL X10**3
14	12A.	45.	1.26	1.3	2.0	79.	.0	10	21.2.1977	40.	3.0	1.0	.35
15	63.	20.	.86	.9	2.7	73.	.0	12	21.2.1977	30.	4.0	.7	.34
16	18.	-10.	.59	.5	2.7	66.	.0	12	21.2.1977	0.	4.1	.5	.33
17	0.	-45.	.47	.4	3.0	67.	.0	12	21.2.1977	0.	4.1	.4	.33
18	0.	-36.	.56	.5	2.4	62.	.0	12	21.2.1977	0.	4.1	.5	.33
19	0.	-31.	.75	.6	3.0	81.	.0	12	21.2.1977	0.	4.0	.6	.33
20	0.	-31.	.81	.6	3.3	83.	.0	12	21.2.1977	0.	3.9	.6	.33
21	0.	-31.	.80	.7	3.6	79.	.0	12	21.2.1977	0.	3.9	.7	.33
22	0.	-31.	.63	.4	2.6	77.	.0	12	21.2.1977	0.	4.0	.5	.33
23	0.	-25.	.50	.4	2.6	66.	.0	12	21.2.1977	0.	4.1	.4	.33

HOUR FROM	SOLAR NET W/M ²	DEP DEG C	SPEED M/S	DIRN DEGS	RAIN MM	GOOD SCANS	LAMBDA*E W/M ²	Q X10 ⁻³	SHO X10 ⁻³	DEL X10 ⁻³
0	0.	.38	.2	90.	.0	12	22.2.1977	4.1	.3	.32
1	0.	.24.	.2	81.	.0	12	22.2.1977	4.2	.3	.32
2	0.	.23.	.2	75.	.0	12	22.2.1977	4.2	.2	.32
3	0.	.22.	.2	7	116.	0	22.2.1977	4.2	.3	.32
4	0.	.24.	.79	.8	2.2	70.	0	4.0	.6	.33
5	0.	.24.	.70	.9	2.4	79.	0	4.1	.6	.34
6	0.	.19.	.40	1.3	2.0	71.	0	4.5	.3	.35
7	10.	.17.	.35	1.5	2.8	75.	0	4.6	.3	.35
8	48.	.3.	.47	1.8	3.7	60.	0	4.6	.4	.36

DAILY CALCULATIONS BASED ON 19 HOURS OF DATA FOR 21 2/1977

.9	.1	.71	1.2	2.6	71.	.5	TOTALS OR AVERAGES BASED ON 5 HOURS OF DAYLIGHT DATA
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TOTAL PENMAN-MONTEITH EVAPORATION FOR DAY IS .28 MJ/M**2, WHICH IS EQUIVALENT TO .11 MM
 ARBDA*E/NET*81
 PENMAN ESTIMATE OF EVAPORATION FOR DAY IS .03MM

FIGURE 2 Sample output of hourly and daily converted data from an automatic weather station in Scotland

MODE = 2 Convert each channel of each scan from logger steps to physical units using the conversion factor(s) appropriate to each channel. For some channels the conversion factor is specified on a data card (ISOLF on card 1 for the solar radiation channel, NETF on card 1 for the net radiation channel, TEMPZ and TMPSEN on card 3 for the temperature channel, DEPSSEN on card 3 for the depression channel and BSIZE on card 3 for the rain channel) and for the others the factors are coded into the program for the four types of weather station in use.

Before the conversion factors are applied to any scan, the scan is checked to be good ie scans with

- (i) zero in all channels (can occur in the first hour of the data if the data does not follow exactly after data from the previous cassette from the same station),
- (ii) scan marks less than 220 or
- (iii) a final channel containing a number greater than 250

are discarded. The analogue channels of each accepted scan are corrected for analogue drift by multiplying their contents by $240/(\text{scan mark})$ after which the conversion factors are applied. RAWD accumulates hourly totals (or averages) by combining the good scans of the 12 possible each hour and corrects the solar radiation total by an amount equal to the total for the period 23.00 → 23.55 of the previous day (0 on first day). The hourly totals (means) are also accumulated into daily totals (means), both for all hours and also for daylight hours (ie hours for which the solar radiation exceeds 5.0 W m^{-2}). RAWD prints out all these totals and the other information calculated in EVAP and PENMAN (q.v.). In addition, if NUNITS > 10 RAWD prints 5 minute data converted to physical units.

- f. CONVRT is a subroutine which does some of the initial work for RAWD in applying corrections to logger steps before conversion to real units; for example, it corrects for zero offsets on the temperature and net radiation channels, and converts the wind run and rainfall channels to differences from the previous scan.
- g. EVAP calculates the Penman-Monteith evaporation estimate using hourly averaged data (see Appendix 2 for more details of the formulae used). It also calculates derived quantities Q (specific humidity), SHD (specific humidity deficit) and DEL (slope of the saturation vapour pressure curve) and λE (the latent heat flux) which are averaged and printed in the same way as the actually measured quantities by RAWD.

- h. PENMAN calculates the PENMAN evaporation estimate using daily averaged data (see Appendix 3 for more details of the formulae and constants used).
- i. ADAY is a subroutine which is called to subtract one day from the current date. This is required for the daily total printout.

4. PROGRAMS FOR OTHER INSTRUMENTS

For some applications, where either there is no scan mark (e.g. rainfall event recorders) or so few channels per scan that writing just one hour's data into a block would be wasteful (e.g. river level recorders⁽⁹⁾ which have four channels per scan), the stage 1 translation is performed with the number-of-channels question mentioned in Section 1 answered by 0. In this case a straight copy of the data on the cassette is made on to the DECTape or magnetic tape with a single -1 appended to it which signals 'end of data' to the second stage FORTRAN program which is used to analyse it. This second stage program also has to detect and deal with faulty scans and perform the type of analysis relevant to the equipment in question.

5. USE OF AN OSCILLOSCOPE DURING TRANSLATION TO DIAGNOSE LOGGING EQUIPMENT MALFUNCTIONS

The early detection of malfunctions in logging equipment is vital to the success of operating weather stations in the field - or indeed any such automatic equipment remote from base. For this reason, a brief discussion of a suitable diagnostic procedure is included here even though this report deals primarily with the software used to translate weather station data. Such a system is complementary to the error detection algorithms discussed in Section 2, not documented elsewhere, and takes place concurrently with the stage 1 cassette translation. The simple expedient of connecting an oscilloscope across the output of the head amplifier of the Microdata reader and watching the waveform as the translation proceeds provides information on malfunctions in the recording process. Normally the waveform should appear as a set of words (each made up of eight bits) separated by small gaps. The sets, which correspond to scans, are terminated by a single extra bit and a larger gap. The amplitude of the signal should be several volts. Some malfunctions give easily recognisable

waveforms as follows:

- i. Last few scans written with the signal amplitude decaying away exponentially from start of scan indicates a flat logger battery.
- ii. Low amplitude signal could mean a dirty logger head or build-up of oxide on head. Signals less than the reader threshold (set to about 1 volt) will lead to data loss.
- iii. Low amplitude rounded signals (normally the bits are sharp spikes) are due to a badly aligned head on the logger or the tape being moved past the head at an angle (skew).
- iv. The number of words per scan should equal the number of channels on the station. The scan mark channel may be only partly written if the logger is "slow off the mark", and sometimes other channels may be badly written or missing due to malfunction of the switching mechanism in the logger.
- v. Scans with too many channels written and all channels zero indicates a battery with a defective cell.
- vi. Regularly varying amplitude may indicate pickup from an external source eg from a mains supply.

Acknowledgements

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APPENDIX 1

Data Cards supplied to FORTRAN analysis program

Card	FORTTRAN Variable	FORTTRAN Format	Parameters Specified
1	MODE	I5	1 for Raw data; 2 for hourly and daily data; 0 to stop.
	ISOLF	I5	Solarimeter calibration factor = 1000/sensitivity in mV/gcal.cm ⁻² min ⁻¹
	NETF	I5	Net radiometer calibration factor = 500/sensitivity in mV/gcal.cm ⁻² . min ⁻¹
	NS	I5	Number of hours of data to be brought forward from previous cassette
	NSS	I5	As NS but for daylight hours
	NOFF	I5	Number of hours to skip before analysis begins
	NH	I5	Number of hours of data to be listed if MODE = 1
2	TITLE	13A6	Station name
3	NTYPE	I5	Type of weather station <ul style="list-style-type: none"> = 1 Standard 8 channel Microdata- Analogue circuits = 2 Standard 9 channel Didcot Instruments - Digital circuits = 3 Thetford hybrid - as 1 with some digital circuits = 4 8 channel stations - digital circuits
	TEMPZ	F5.1	Number of logger steps corresponding to 0°C on temperature channel
	DEPSEN	F5.3	Sensitivity of depression channel in °C per logger step
	NDAYFP	I5	Hour of day at which daily totals are calculated
	NUNITS	I5	Index for system of units to be used (not used). If > 10 and MODE = 2, converted 5 minute data are printed.

Continued

Card	FORTTRAN Variable	FORTTRAN Format	Parameters Specified
	TMPSEN	F5.3	Sensitivity of temperature channel in °C per logger step
	BSIZE	F5.1	Raingauge bucket size in mm
4	IRS(24)	Free	Array of hourly r_s values (stomatal resistance) in sec. m^{-1}
5	RA	Free	Aerodynamic resistance r_a in sec. m^{-1}
	AK	Free	Psychrometric constant (= 1232 for screen in units of program)
	ALT	Free	Station altitude in metres
6	IHOUR	I2)	Start time and date for cassette
	MINS	I2)	
	NDAY	I2)	
	MONTH	I2)	
	NYEAR	I4)	
7	DAYSUM (7)	Free	Data brought forward from previous cassette. Totals for NS hours
8	SAYSUM (7)	Free	As 7 but for daylight hours data for NSS hours

Note cards 7 and 8 are omitted if MODE = 1 or NS = 0

APPENDIX 2

The Penman-Monteith evaporation flux is given by

$$\lambda E = \frac{\Delta A + \frac{\rho c_p}{r_a} (SHD)}{\Delta + \frac{c_p}{\lambda} \left(1 + \frac{r_s}{r_a}\right)}$$

Where Δ is the slope of the specific humidity curve at dry bulb temperature,

A is the available energy for evaporation and net radiation is used.

ρ is the density of air set to 1.20 Kg m^{-3} in the program

c_p is the specific heat of air at constant pressure and set to $1.01 \times 10^3 \text{ J Kg}^{-1} \text{ }^\circ\text{C}^{-1}$

SHD is the specific humidity deficit at dry bulb temperature,

ie. $SHD = QW - Q$

where QW is the saturated specific humidity at dry bulb temperature and Q is the specific humidity of the air.

QW is calculated from ⁽⁶⁾

$$QW = 0.62197 / \left(\frac{P}{1.0045 \text{ SVP}} + 0.62197 - 1 \right)$$

Where P , the standard atmospheric pressure at the altitude at which the weather station is positioned (h metres), is given by ⁽⁵⁾

$$P = 1012 \left(1 - \frac{0.0065h}{288} \right)^{5.2553} \text{ mb.}$$

and SVP, the saturated vapour pressure is calculated from ⁽⁶⁾

$$\text{SVP} = 17.044 + T' (5.487 + T' (0.776 + T' (0.063 + 0.003T')))$$

Where T' is $\frac{T}{5} - 3$ where T is the dry bulb temperature in $^\circ\text{C}$

APPENDIX 3

The daily potential evapotranspiration E_T in mm is calculated from the Penman formula

$$E_T = \frac{\Delta H_T}{\Delta + \gamma} + \frac{\gamma E_a}{\Delta + \gamma}$$

where H_T is the heat budget in mm water equivalent, that is the net energy available at the surface from which the evaporation is to be estimated to act as the energy source for evaporation, and E_a is the 'aerodynamic term' in mm water equivalent which reflects the fact that ventilation is required to sustain evaporation once the air at the surface becomes saturated. Δ and γ are 'efficiency factors' which govern the relative effects of energy supply and ventilation⁽²⁾. Δ is the slope of the vapour pressure curve for water at mean air temperature, and γ is the psychrometric constant. This equation was intended for use only for short green crops.

H_T is calculated from the net radiation R_N in cal. cm^{-2} using

$$H_T = R_N / L$$

where L is the latent heat of vaporization of water and related to the dry bulb temperature, T_D as follows:

$$L = (60.74 - 0.0314 T_D) \text{ cal mm}^{-1} \text{ cm}^{-2}$$

E_a is calculated from

$$E_a = 0.35 \left(1 + \frac{u_2}{100} \right) (e_a - e_d) \times k$$

where u_2 is the wind run in miles per day

e_a is the saturation vapour pressure in mm Hg

e_d is the actual vapour pressure in mm Hg

and k is a pressure correction for altitude⁽³⁾ given

$$\text{by } k = 1 + \frac{h}{20000} \text{ where } h \text{ is the station altitude in m.}$$

e_a and e_d are calculated from the daily mean dry bulb temperature T_D in $^{\circ}\text{F}$ and the daily mean depression D . The daily mean wet bulb temperature is given by $T_W = T_D - D$. The following polynomials expansions⁽⁴⁾ are used to evaluate e_a

$$e_a = ((3.312 \times 10^{-5} T_D + 8.128 \times 10^{-4}) T_D + 0.05352) T_D + 0.9479$$

for $T_W \leq 32^{\circ}\text{F}$

$$\text{or } e_a = (((3.98647 \times 10^{-7} T_D - 2.90916 \times 10^{-5}) T_D + 3.96084 \times 10^{-3}) T_D - 0.034111) T_D + 2.1565$$

for $T_W > 32^{\circ}\text{F}$

e_d is calculated from the psychrometric equation

$$e_d = e_w - 0.3(T_D - T_W)$$

where e_w is calculated using the same polynomials as used for e_a with T_W substituted for T_D .

Δ in $\text{mm Hg } ^{\circ}\text{F}^{-1}$ is calculated from

$$\Delta = (9.936 \times 10^{-5} T_D + 1.6256 \times 10^{-3}) T_D + 0.05352 \quad T_W \leq 32^{\circ}\text{F}$$

$$\text{or } (1.594588 \times 10^{-6} T_D - 8.72748 \times 10^{-5}) T_D + 7.92168 \times 10^{-3}) T_D - 0.034111$$

for $T_W > 32^{\circ}\text{F}$

γ in $\text{mm Hg } ^{\circ}\text{F}^{-1}$ is calculated from⁽⁵⁾

$$\gamma = 0.0002727 \times 1012 \left(1 - \frac{0.0065h}{288}\right)^{5.2553}$$

The Penman estimate of evaporation can be evaluated by substituting these values in the first equation.